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Reversible operation of a high current superconductor switch based on the quench of high-resistance second generation high temperature superconducting wire is demonstrated. The quench is induced by a burst of an ac field generated by an inductively coupled radio-frequency coil. The switch makes a superconducting-to-normal transition within 5 ms and also has a rapid recovery to the superconducting state. The device has potential applications as an active current limiter or as a storage switch for superconducting magnetic energy storage systems. Operation in a full flux penetration/flow regime can effectively minimize the detrimental effects of the intrinsic conductor non-uniformity. © 2013 AIP Publishing LLC. [http://dx.doi.org/10.1063/1.4813883]

An appealing feature of superconductor switching devices is their near zero resistance, which allows a scale-up of the device to a high operating voltage and current without the penalty of added conduction losses. A superconductor element transitions from the superconducting (zero resistance) state to the normal state (more generally, resistive state) when any one of three factors: (i) temperature, T, (ii) current density, J, or (iii) magnetic field, B, exceeds a certain critical value. These superconductor properties are widely utilized for detector,[1] electric power,[2] and superconducting magnet applications.

The superconducting-to-normal transition in a fault-current limiter (FCL) utilizes the second ambient factor, transport current.[3–5] The transition is triggered when the current density at a given temperature and magnetic field exceeds the critical current density, J_c. Since there is no external heating involved, the transition time can be very short, less than 10 ms. The availability of long-length (hundreds of meters) second generation (2G) $YBa_2Cu_3O_7$ (YBCO) superconducting wire[6] has enabled the practical designs of in-grid FCLs operating at 77 K.[7] The transition threshold of a FCL is determined by the lowest J_c in the whole conductor. The transport properties of YBCO are highly sensitive to the local microstructure, hence the J_c of 2G wire is non-uniform both along and across the tape.[8] In order to avoid damage to the conductor due to the non-uniformity of the superconducting-to-normal transition, the superconducting element needs to be coated with a normal metal (stabilizer), which substantially reduces the off-resistance of the switch and raises the thermal mass of the device.

We have developed a fast high-current switching device that relies on the rapid superconducting transition of the material to the normal state. This transition is induced by a radio-frequency (RF) field created by a compact flat coil which is inductively coupled to the superconducting layer. This design retains the positive features of a FCL, while minimizing the adverse effect of conductor non-uniformity, which potentially enables the attainment of high off-resistance values.

Fig. 1(a) is a schematic rendering of the device and Fig. 1(b) is its equivalent electrical diagram of the device. A switching superconductor element (R1) is tightly wrapped around a flat RF coil (L1) manufactured from 18 gauge, 175 strand Litz wire. The switching element R1 was manufactured from a 1 m long piece of commercially available YBCO tape (SuperPower Inc.). The middle 50 cm of the tape was stripped of the stabilizing layers by a chemical etch, yielding the total element resistance of 1.2 Ω. In the superconducting state, the tape resistance to dc electric current generated by the power source I1 is zero. This corresponds to the "on" state. In order to turn the device "off" (the non-superconducting state of the superconductor element R1), a RF generator V1 applies a high-frequency ($f = 100$–500 kHz) voltage burst (up to 100 ms long) to the coil L1. Large inductive currents are excited in the superconductor due to the strong coupling of the coil to the superconducting layer. The transition to the normal state is triggered whenever the superposition of inductive and dc currents exceeds the critical current density of the superconducting tape. The superconducting-to-normal transition is further assisted by hysteretic losses induced by the fast-changing fields and Joule losses due to the rising voltage of the current source I1. The by-pass MOSFET switches Q3 and Q4 (International Rectifier, model IRF1324S-7PPBF) were mounted directly on the tape by the drain leads in order to provide a low-resistance current by-pass during the normal-to-superconducting transitions. Closing of the MOSFETs Q3 and Q4 in the "off" state of R1 allowed switch cool-down and transition to the superconducting "on" state, thus, completing the cycle of operation.

Fig. 2(a) presents the results of a calibration experiment intended to determine the threshold RF power required to drive the superconducting tape into the normal state. The RF power level is proportional to the square of the peak-to-peak voltage on the coil. The I-V curves of a short tape coupon are recorded at various RF power levels. We observed a superconducting-to-normal transition at >7 V peak RF amplitude. In the following experiments, we applied the RF power at 10 V, i.e., exceeding the threshold by ~20%.

Fig. 2(b) shows of the RF-assisted transition speed of a switch operating at 65 A. The RF burst at 10 V peak-to-peak amplitude is applied for 5 ms. During the RF burst application, the switch tape is by-passed by the closed MOSFETs. After the application of the RF burst, the MOSFETs are opened and the current immediately drops from 65 A to 10 A, dropping to 3 A in 10 ms. The "off"
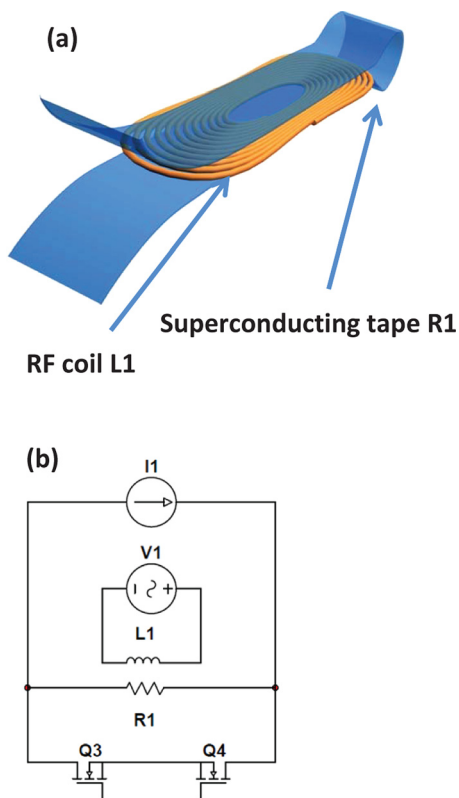
FIG. 1. (a) Conceptual drawing of the RF-assisted superconducting switch. (b) An equivalent electric diagram of the device.
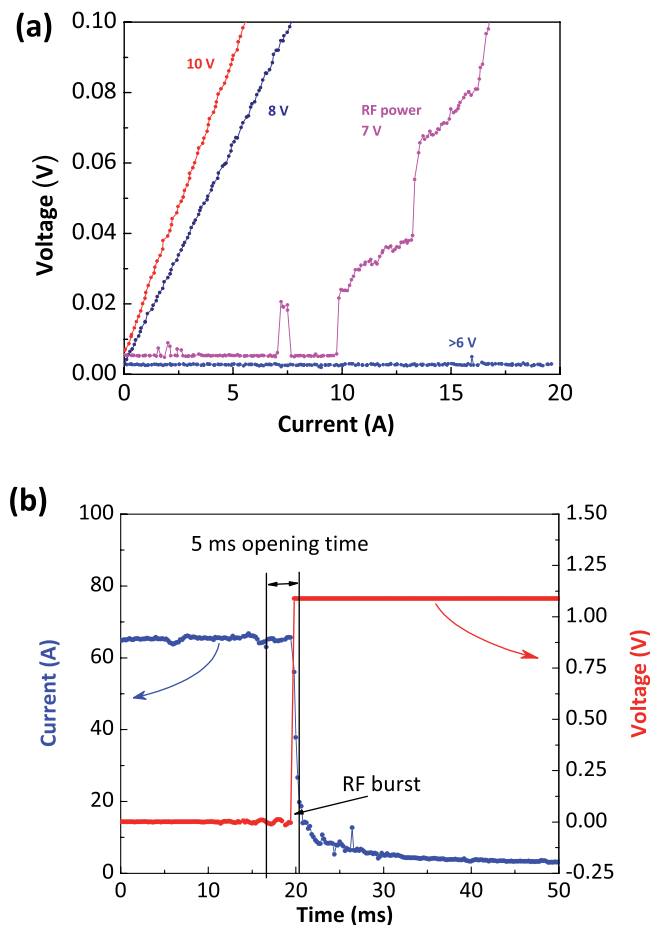

FIG. 2. (a) Static I-V curves of a superconducting tape at various RF power levels (in volts on the coil). (b) Opening of the switch is induced by a 5 ms RF burst. Note that the opening time is under 5 ms.

current level is based on the 1.2 Ω normal state resistance of the switch.

A complete cycle of operation is shown in Fig. 3(a). Here, a 100 ms RF burst was applied to the switch operating at various current levels, from 10 to 90 A, at a fixed voltage of 0.2 V. The switch stayed in the "off" position for 1 s, followed by closing of the MOSFET by-pass for 100 ms and transition of the switch to the superconducting state. A set of waveforms in Fig. 3(b) shows the operation of the switch and the fixed-current level. We observe a reversible operation up to the limit of the power supply (6 V).

Device operation is based on inducing a uniform quench of the stabilizer-free 2G wire. Without the uniform quench, the normal zone would not have time to spread until the conductor is damaged, due to the exceptionally low rate of normal zone propagation in YBCO, about 1-2 mm/s.[9,10] Studies of unprotected quenches demonstrate that the degradation of the YBCO layer occurs at $T \approx 490$ K, primarily because of a high level of thermal stress.[11] Conductor damage can be avoided if the superconducting layer switches to the normal state uniformly, both along and across the tape, within a short time, $t < 200$ ms.[11] Our approach for creating a uniform normal zone has two components. First, the full penetration of the ac magnetic field into the tape assures the uniformity of the normal zone across the tape. Second, the frequency of the ac field is high enough to attain the flux flow regime, which minimizes the effect of the longitudinal non-uniformity of the tape.

The following estimation shows that the full ac field penetration into the superconductor can be accomplished using a lightweight flexible coil. The interaction of a thin YBCO layer with an external ac field has been theoretically studied by Brandt.[12,13] In a strongly coupled geometry, shown in Fig. 1(a)), an easier approach would be to treat the interaction between the coil and the superconductor by introducing an image current. The average sheet current in the coil would induce a mirror current in the superconductor (the image current being superimposed on the transport current). Even though the current density of YBCO is several magnitudes higher than that of copper, the equivalent sheet current density can be attained due to the larger copper cross-section: 1.2 μm YBCO vs. 1.02 mm for gauge 18 wire. For an eight-turn coil excited by a current of 40 A, the sheet current density is 320 A/cm, which is comparable with the critical current, I_c, of the wire, at $\sim$350–380 A/cm.

Full field penetration assures the cross-wise (normal to the tape length) transition to the normal state. However, 2G wires are also non-uniform along the tape length on the mm and μm scales.[8] The effect of the normal zone infirmity non-uniformity becomes critical when we consider the energy balance between the energy dissipation in the superconductor and the heat removal by boiling nitrogen. A pool of boiling nitrogen can efficiently remove up to $\approx$10 W/cm^2 of heat flux from a solid surface.[14] The switch shown in Fig. 1 dissipates approximately 30 W in the normal state. If we assume a uniform dissipation, the average heat flux is $\approx$0.5 W/cm^2, which well within the safety margin for boiling nitrogen. However, concentration of the same power in an area smaller than 2 cm^2 would lead to runaway overheating.
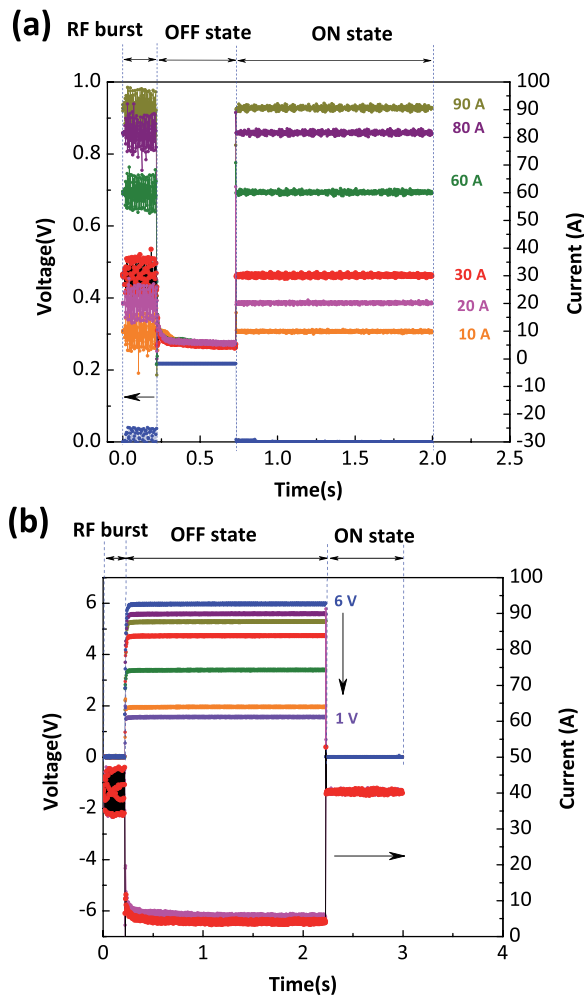
FIG. 3. Operation of RF-assisted switch at: (a) various current levels 10–90 A, fixed voltage 0.2 V (b) various voltage levels, current fixed at 40 A.

Heat generation in a classic type II superconductor in the mixed state, i.e., $J > J_c$, is explained by the viscous motion of magnetic flux lines. The electric field strength E created by the vortex motion is described by the Bardeen-Stephan equation,[15] $E = \rho_f (J - J_c)$, where ρ_f is the flux flow resistance.[16] The flux flow regime can be described as a region in the I-V plane of a superconductor where the driving current J is much larger than J_c, so that the electric field strength depends more on vortex-vortex interactions, and less on the interaction between the vortices and the defects of the material. In this regime the local dissipation is proportional to the driving current amplitude, which in this case is determined by the RF coil excitation and the normal state resistance of the superconductor. The normal state resistance is by far the most uniform property of the superconductor, because, unlike J_c, it is weakly affected by local variations of pinning strength and grain connectivity. Therefore, a transition based on dissipation in the flux flow regime would provide the best lengthwise uniformity and the smallest chance for causing damage to the superconductor during the quench.

The minimum ac field frequency required to attain a uniform flux flow along the tape can be estimated using typical I-V curves of coated conductors.[17] We determine that the

flux flow regime corresponds to the AC electric field strength $E_{ac} = a \, dB_{ac}/dt$ (here, $a = 12$ mm is the tape width and B_{ac} is the AC magnetic field) on the order of 1 V/cm. Considering that B_{ac} is approximately equal to the penetration field, we estimate that the electric field strength of 1 V/cm is achieved at $f \sim 200$ kHz. Thus, a high-power, high-frequency RF coil operating at $f > 100$ kHz is capable of driving a long superconducting tape into a normal state uniformly in both the longitudinal and transverse directions.

In conclusion, we describe a superconducting switching device gated by an inductively coupled radio-frequency coil. The operational principle is based on the rapid generation of a large-area uniform normal zone, which enables fast off-switching and recovery. In this design, the lower limit of the off-resistance of the device is imposed by the Hastelloy substrate. Further improvements of the off-resistance can be accomplished by isolating the superconductor layer from the metal substrate by a high-breakdown dielectric layer. This technology could enable development of a compact superconducting switching device suitable for power applications such as a superconducting breaker or a re-closer.

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